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## A long time-series verification of hindcasts from the Meteorological Office wave model archive

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**Summary**

Wave height data from the Meteorological Office fine-mesh wave model hindcast archive are compared with measured wave data at three stations in the west of Great Britain. The results are discussed with time series and graphs of error statistics.

### 1. Introduction

The purpose of this study was to compare some products of the Meteorological Office wave forecasting model (Golding 1983) with instrumentally measured wave data. The archived model data are available for a period of nearly five years, 1 January 1978 to 26 September 1982. During this time the model was being continually improved and the principal dates in its development are given in Table I. Since 26 September 1982 the model has been transferred from the IBM 360/195 computer to run operationally on the Cyber 205 machine. At the same time the computation grid length was decreased from 50 km to 25 km and the atmospheric forecast model which provides the basic forecast winds was also improved.

Insufficient real-time measured wave data are available, hence a hindcast technique is used in place of a wave analysis in the operational cycle. It is these hindcasts of sea state that comprise the archive. A hindcast is started from a wave field generated at *T*-12, using winds from an atmospheric forecast made 12 hours earlier. These winds are adjusted using pressure analyses every 6 hours and wind analyses every 3 hours. This process gives the best available estimate of the actual wind conditions during the past 12 hours. The accuracy of the archived hindcasts depends on the accuracy of the hindcast winds and on the predicting skill of the wave model itself. For the purpose of this study the winds are assumed to be adequately represented, and therefore any errors identified will be attributed to the wave model prediction processes.

All data sources used are in the west of Great Britain and thus consist of wind-sea and Atlantic swell components. The swell contribution may have, in reality, been generated outside the fine-mesh grid area and would be specified as boundary conditions derived from a forecast run of the coarser-mesh Atlantic wave model. For this reason the model swell contribution may be of poorer quality than the wind-sea.

**Table I.** *Principal dates in the development of the wave model*

| Date | Development | Effect |
|---|---|---|
| 18/07/78 | Surface wind analysis introduced | Better hindcast winds |
| 26/09/78 | Shallow-water friction term introduced | Lower wave heights in shallow water |
| 23/10/79 | Wave growth includes JONSWAP spectrum | More realistic wave growth |
| | 11 frequencies | Higher-resolution wave spectrum |
| 18/03/80 | Dissipation coefficient increased | Greater attenuation of swell and slower wave growth |
| 14/04/81 | Modification of archived spectrum representation | More accurate storage of high-frequency wave energy components |

## 2. The measured data sources

Instrumentally measured data were supplied by the Marine Information and Advisory Service (MIAS) of the Institute of Oceanographic Sciences (IOS). Three sites were used: Isles of Scilly waverider buoy, South Uist waverider buoy and St. Gowan light-vessel shipborne wave recorder. Locations are as shown in Fig. 1. A fourth site at Channel light-vessel was rejected because of possible errors in the data caused by marine fouling of the recording instrument. The periods of data availability are shown in Table II.

Archived model data are available only at 00 and 12 GMT; measured data are available every three hours on average although not always on the hour.

The IOS data are considered reliable, as quality control is exercised on all data that enter the MIAS data banks.

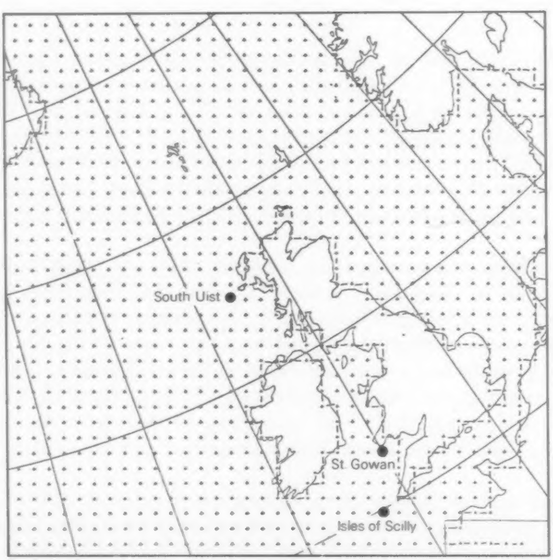


Figure 1. Grid points of the fine-mesh wave area and sites used in this study.

The wave forecast model is based on a polar stereographic grid and data are available only at these grid points. The positions of the instrument sites and corresponding model grid points are given in Table III.

As noted above, two sites used waverider buoys (WRB) to measure wave height while the third used a shipborne wave recorder (SBWR). The WRB contains an accelerometer which measures the vertical displacement of the buoy and records the variability of the surface elevation about the mean sea level. The SBWR uses two pairs of accelerometer and pressure units which are situated one on each side of the ship approximately on the pitch axis. For wavelengths longer than the length of the ship the SBWR measures vertical displacement like the WRB. For wavelengths shorter than the length of the ship the pressure units record variations in pressure as the waves pass.

Work has shown that there are differences in the results of these devices (Graham *et al.* 1979). On average the SBWR measures wave heights as 8% higher than the WRB. The percentage is greater for low waves and smaller for high waves; indeed heights measured by SBWR can be as much as 14% greater than heights measured by WRB for 1 m waves.

**Table II.** *Dates of available data and periods used at each site*

| Site | Period of available data | Period used |
|---|---|---|
| Isles of Scilly | 11/02/80 – 31/12/81 | 02/80 – 12/81 |
| South Uist | 15/08/80 – 31/12/82 | 08/80 – 01/82 |
| St. Gowan | 01/01/77 – 31/12/81 | 01/78 – 12/81 |

**Table III.** *Positions of sites and of corresponding model grid points*

| Site | Site position | Grid-point position |
|---|---|---|
| Isles of Scilly | 49°51.8′N 06°41.0′W | 49°54′N 06°18′W |
| South Uist | 57°17.8′N 07°53.6′W | 57°24′N 08°06′W |
| St. Gowan | 51°30.5′N 04°59.8′W | 51°24′N 05°00′W |

## 3. Analysis of data

At each site time-series plots of wave height for each month were drawn by computer, each plot comparing model and instrumentally measured data. Before input into the graph-drawing program the record times of the measured data were converted to the nearest hour. Initially all data were used to produce the time-series plots and these showed considerable fluctuations in the measured time series between data points on the model time series (see Fig. 2). These fluctuations can be masked if only measured data with record times within an hour of model data points are used; this can be seen in Fig. 3.

The model archive does not purport to represent wave heights at times other than 00 and 12 GMT, so the latter time series offers a better comparison; however, as the first time series shows, the wave field is changing on a much smaller time scale so it will be of use to consider both representations of the measured time series.

Various statistics were also produced at each site; for these only data with coincident record times were used. As the statistics were compiled on a monthly basis this procedure reduced the number of observations to a maximum of 62 and any month with fewer than 20 observations was rejected. The main outcome of these statistics is shown as plots of mean and root-mean-square (r.m.s.) error for each month and graphs of mean and r.m.s. error against mean observed height.

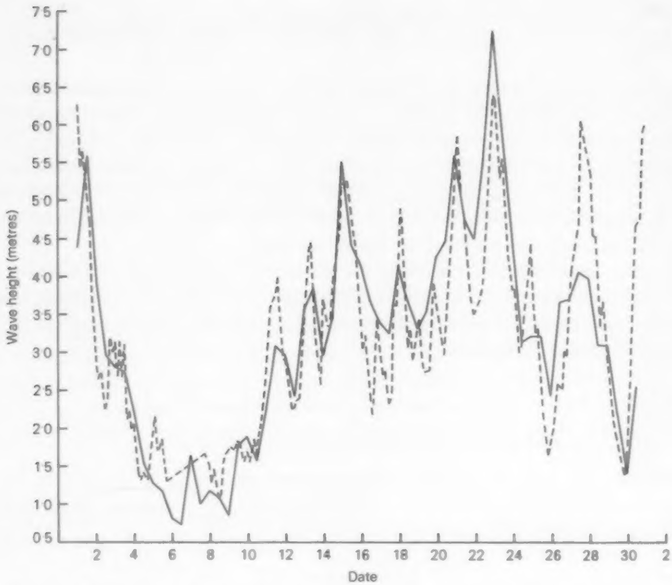


Figure 2. Time series of wave heights at South Uist for November 1980, using all data.
——— model data – – – measured data

## 4. Results

Considering first the plots of r.m.s. and mean error (Figs 4(a), (b) and (c)), it can be seen that for the periods shown all sites have a monthly mean error of less than 1 m while for South Uist and the Isles of Scilly it is less than 0.4 m.

An interesting feature to note at the St. Gowan site is that the sign of the mean error changes from being mainly positive to mainly negative after October 1979. The exact time of the change cannot be found because instrumental data are not available for the whole of the period in question. There were, however, a number of major wave-model changes implemented around that time.

These changes were designed to modify the wave-growth curve and the effect was to lower wave heights for high wind speeds and short fetches. The fetch at St. Gowan in a westerly direction is approximately 200 km and for low wind speeds (e.g. 10 m $s^{-1}$) the modelled waves from this direction become fully developed both before and after the change in formulation, so there was little effect on low waves because of this change.

From Fig. 5, which depicts dimensionless growth rate as a function of dimensionless fetch, it can be shown that significant wave height, $H_s$, = 6.9 m for a 20 m $s^{-1}$ wind over 200 km in the pre-October 1979 model. Also from Fig. 5 it can be shown that $H_s$ = 4.9 m for a 20 m $s^{-1}$ wind over 200 km in the post-October 1979 model. So at high winds (high waves) the change in the model should be manifested by a drop in modelled wave heights of about 1 or 2 metres. This fact explains an anomalous previous verification exercise for data from Kinsale Head (51° 30′N, 7° 55′W) and suggests that short-fetch wave growth is too low in the post-October 1979 model, even though it now agrees well with results from the

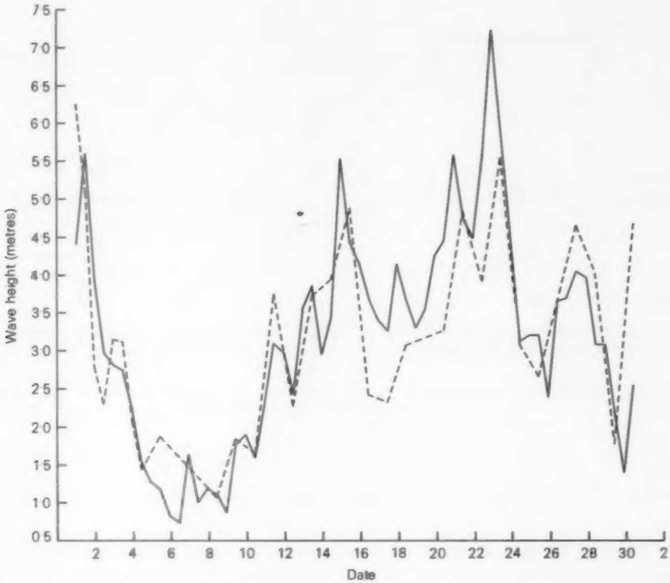


Figure 3. Time series of wave heights at South Uist for November 1980, using only data for 00 and 12 GMT.
——— model data – – – measured data

Joint North Sea Wave Project (JONSWAP), which measured wave growth in the North Sea (Hasselmann *et al*. 1973).

There seems to be some seasonal variation in mean error at St. Gowan but not at the Isles of Scilly and South Uist (Fig. 4(c)). This variation takes the form of smaller errors in 'summer' and larger errors in 'winter'. An associated relationship is found in the plots of mean error against mean observed wave height for St. Gowan (Fig. 6(c)). These show a roughly linear relationship before the change in October 1979, with large wave heights associated with high positive mean errors and a similar linear relationship after October 1979 but with large wave heights associated with large negative mean errors. These relationships are explained by the representation of low waves not being affected by the modelling change while the modelled high waves were greatly reduced in short-fetch situations.

This diagnosis can be further confirmed by considering two months (June and October 1981) at St. Gowan. June has a small mean error while October has a large negative mean error. Analysis of the wind direction for these months reveals the distribution shown in Table IV. When the wind direction is between north and west, St. Gowan is sheltered by Ireland and waves have only a short fetch, and are mostly high-frequency wind waves. For wind directions between south and west, waves have a long fetch and are mainly low-frequency Atlantic swell. In winter the wind is mainly from the sector from north to west, giving shorter fetches.

This wind distribution therefore explains the seasonal variation, with the mean error more negative in winter than in summer after October 1979 owing to under-forecasting in short-fetch conditions and the reverse applying before October 1979. Also the absence of a seasonal variation in mean error at the other

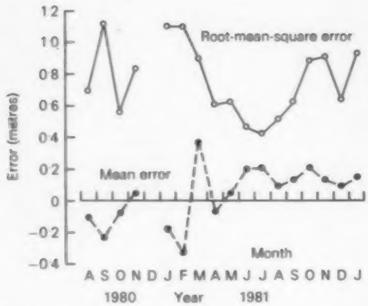


Figure 4(a). Root-mean-square and mean errors of model against observed wave height for each month at South Uist.

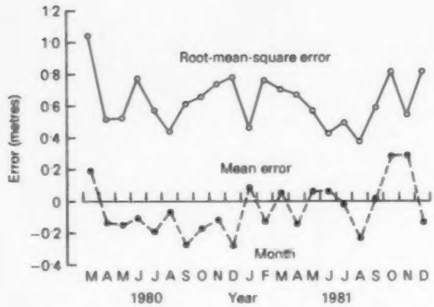


Figure 4(b). Root-mean-square and mean errors of model against observed wave height for each month at Isles of Scilly.

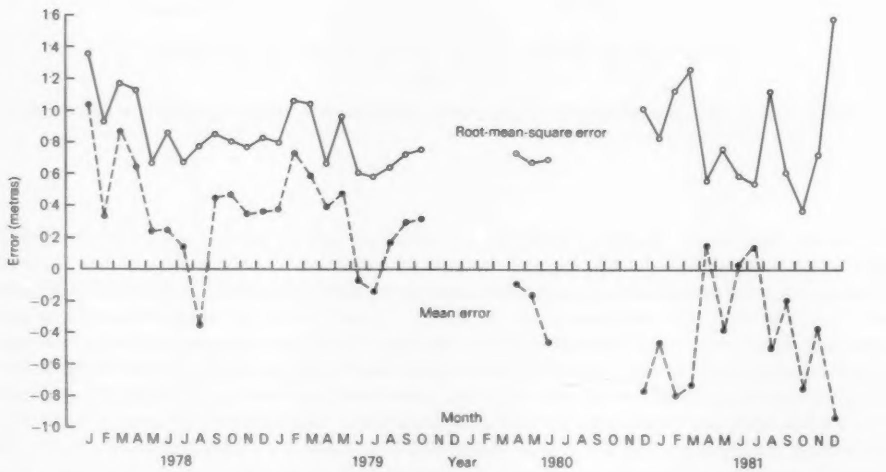


Figure 4(c). Root-mean-square and mean errors of model against observed wave height for each month at St. Gowan.

**Table IV.** *Number of occasions during two months when the wind was blowing from each sector at St. Gowan*

| Month | Sector | |
|---|---|---|
| | north-west | south-west |
| June 1981 | 17 | 27 |
| October 1981 | 27 | 20 |

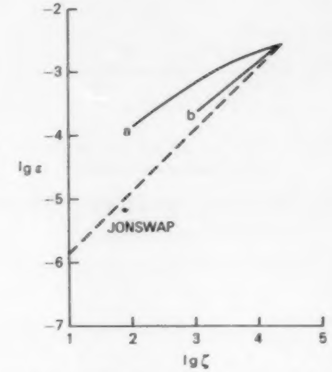


Figure 5. Dimensionless wave-growth rate ( $\epsilon$ ) as a function of dimensionless fetch ( $\zeta$ ) for before October 1979 (a), after October 1979 (b) and in the Joint North Sea Wave Project (JONSWAP).

$\epsilon = \frac{g^2}{u^4} E$, $\zeta = \frac{g}{u^2} x$ and $H_s = \sqrt[4]{E}$,

where $g$ = 9.81 m s$^{-2}$, $u$ = wind speed (m s$^{-2}$), $E$ = wave energy (m$^2$), $x$ = fetch (m) and $H_s$ = significant wave height (m).

two sites (Figs 6(a), (b) and (c)) would be explained by the fact that they both enjoy a long fetch for prevailing wind directions and hence were not affected by the modelling change.

The r.m.s. errors for the Isles of Scilly and South Uist are again fairly good (Fig. 4), with those at the Isles of Scilly being mainly less than 0.8 m and those at South Uist being less than 1.2 m. St. Gowan's largest error is less than 1.6 m but in the main this site also has an r.m.s. error of less than 1.2 m.

There also seems to be some slight seasonal variation in r.m.s. error, again with smaller errors in the 'summer' and larger errors in the 'winter'. The idea that this is associated with waves in summer being generally smaller than in winter is strengthened by the plots of r.m.s. error against mean observed wave height (Figs 7(a), (b) and (c)). These seem to show an approximate linear relationship with higher mean observed waves giving higher r.m.s. errors.

Table V gives the mean and r.m.s. errors for the whole period of the verification exercise at each site.

The measured data at St. Gowan seem very variable, for example December 1978 (Figs 8(a) and (b)) compared to the other sites (e.g., Fig. 2). The period of these oscillations was checked in months with little model variability and was found to be about 12 hours. This is also the approximate time between high tides and between times of maximum current flow. Table VI gives values of current range and tidal range at each of the three sites (Hydrographer of the Navy 1961, 1969, 1978).

It is possible to estimate the effect of tidal current on wave height using Fig. 9 and an estimation of its parameters. Using the deep-water approximation for wave velocity,

$$C_0 = \frac{gT}{2\pi},$$

where $C_0 \approx 10$ m s$^{-1}$ for typical-period waves and if $v \approx \pm\ 1$ m s$^{-1}$ from the mean tidal current velocity range at St. Gowan (Table VI), then $v/C_0 \approx \pm\ 0.1$ and $0.9 \leqslant H/H_0 \leqslant 1.25$ for a typical situation at St. Gowan. The amplitude of the tidal modulation of wave height is about $0.35H_0$ which is about 1 m when the undisturbed wave height ($H_0$) is about 3 m. This calculation is in reasonable agreement with the oscillations shown in Fig. 8(a) which have a period of 12 hours and an amplitude of approximately 1 m.

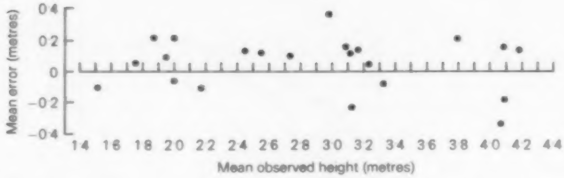


Figure 6(a). Mean error against mean observed wave height at South Uist.

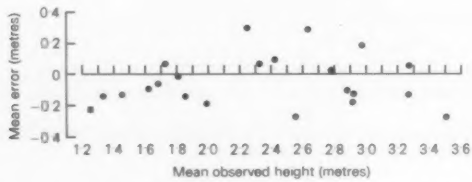


Figure 6(b). Mean error against mean observed wave height at Isles of Scilly.

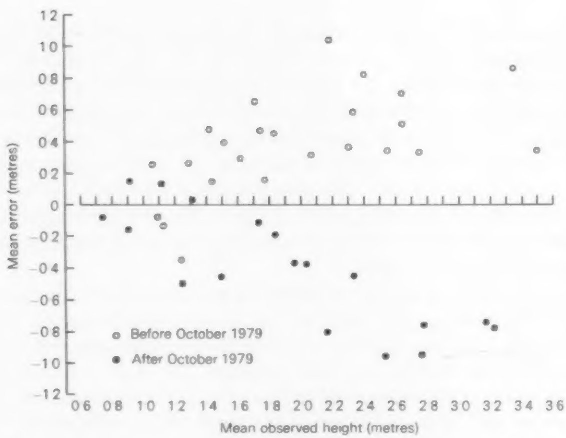


Figure 6(c). Mean error against mean observed wave height at St. Gowan.

**Table V.** *Mean and root-mean-square errors for each site for the stated periods*

| Site | Period | Mean error (m) | R.m.s. error (m) |
|---|---|---|---|
| South Uist | 02/80 – 12/81 | 0.05 | 0.73 |
| Isles of Scilly | 08/80 – 01/82 | −0.05 | 0.63 |
| St. Gowan | 01/78 – 12/81 | 0.03 | 0.89 |
| St. Gowan | 01/78 – 10/79 | 0.36 | 0.86 |
| St. Gowan | 10/79 – 12/81 | −0.38 | 0.93 |

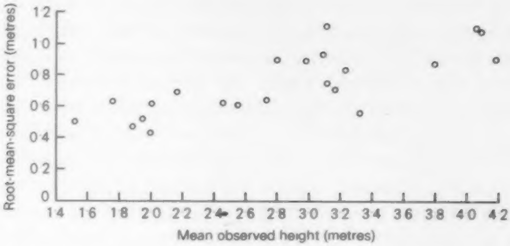


Figure 7(a). Root-mean-square error against mean observed wave height at South Uist.

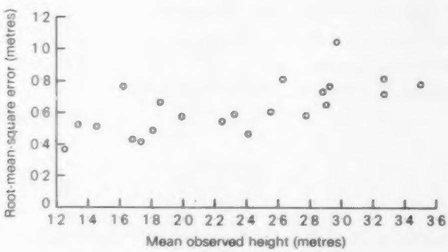


Figure 7(b). Root-mean-square error against mean observed wave height at Isles of Scilly.

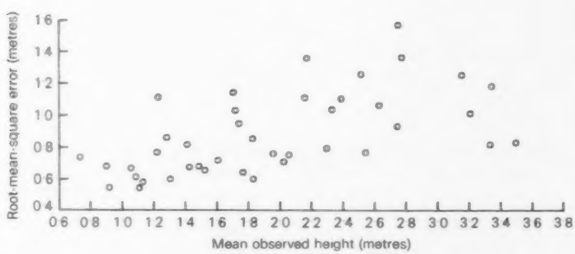


Figure 7(c). Root-mean square error against mean observed wave height at St. Gowan.

**Table VI.** ***Values of current and tidal range for each site***

| Site | Spring/ Neap | Tidal range (m) | Current in (kn) | Current out (kn) | Current range (kn) |
|---|---|---|---|---|---|
| South Uist | S | 3.8 | 0.4 | 0.4 | 0.8 |
| | N | 1.7 | 0.2 | 0.2 | 0.4 |
| St. Gowan | S | 6.3 | 2.5 | 2.2 | 4.7 |
| | N | 2.7 | 1.4 | 1.2 | 2.6 |
| Isles of Scilly | S | 5.0 | 1.5 | 1.5 | 3.0 |
| | N | 2.3 | 0.8 | 0.8 | 1.6 |

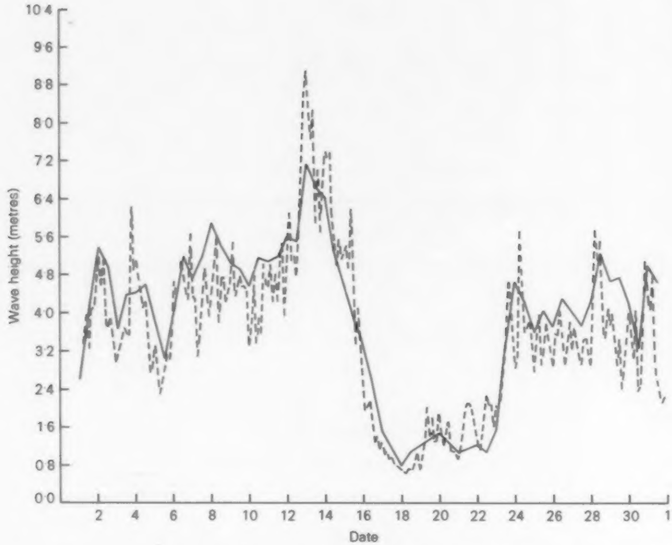


Figure 8(a). Time series of wave heights at St. Gowan for December 1978, showing great variability in the measured data.
——— model data – – – measured data

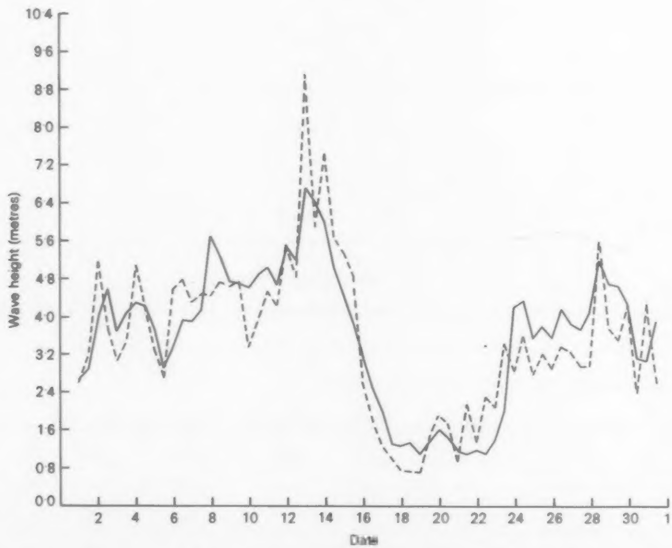


Figure 8(b). Time series of wave heights at St. Gowan for December 1978, using only data for 00 and 12 GMT.
——— model data – – – measured data

This analysis seems to support the idea that the small-scale oscillations in the measured data at St. Gowan are due to tidal currents. The current at St. Gowan is much stronger than at the other sites and this may be why there are no marked fluctuations in the measured data at the Isles of Scilly and South Uist. As the wave model does not include the effects of current this may be one reason why the verification statistics at St. Gowan are worse than those of the other sites. There should be some change in the amplitude of the oscillations due to spring and neap tides but it is not possible to identify this, usually because it is hidden by the natural variability of the measured wave height.

It should be remembered that the measuring instrument at St. Gowan site is a shipborne wave recorder (SBWR) whereas at the other sites there are waverider buoys (WRB) which tend to be viewed as the more accurate instrument. As mentioned earlier, SBWRs measure wave heights higher than WRBs by as much as 14% for 1 m waves and 8% for 4 m waves, and if we were to accept the WRB as an absolute standard for wave measurements it would be possible to correct the SBWR data at St. Gowan by these factors. The result would be to add between 0.1 and 0.2 m to the mean error distribution at this station shown in Fig. 6(c), which would improve the results from the post-October 1979 model but not remove the bias completely. It is possible that some of the errors apparent at St. Gowan can be attributed to the measuring device employed there, but given the complex nature of the true and the modelled wave climate at this location it is clear that there are many contributing sources of error which cannot be individually identified and isolated.

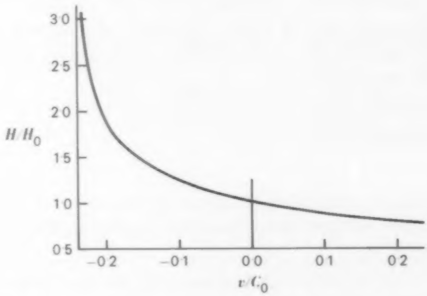


Figure 9. Change in wave height in an opposing or following current (Scripps Institution of Oceanography 1944). $H_0$ = wave height in still water, $H$ = wave height in current, $C_0$ = wave velocity in still water and $v$ = velocity of current — positive for following, negative for opposing.

## 5. Conclusions

The aim of this study was to compare the Meteorological Office IBM wave model archive with instrumentally measured wave data. Three sites were chosen at which reliable measured data were available.

The Isles of Scilly and South Uist sites were very similar in that they were both exposed stations in deep water (100 m and 96 m respectively) with small tidal effects, and data were collected by waverider buoy. Data were available for 17 months at South Uist and 21 months at the Isles of Scilly. The verification results were fairly similar, with mean errors for these periods being 0.05 m and −0.05 m and r.m.s. errors being 0.73 m and 0.63 m, for South Uist and the Isles of Scilly respectively.

The model thus appears to agree well with measurements in deep water and exposed locations, and displays no bias of mean wave-height error over any of the height ranges compared. The r.m.s. error, however, is found to increase with height.

St. Gowan was a station with a varying fetch (depending on the wind direction) in shallow (49 m) tidal water, and data were collected by shipborne wave recorder. Three years of data were available and gave results for the period of mean error 0.03 m and r.m.s. error 0.89 m. The mean errors at St. Gowan change greatly after October 1979, from 0.36 m to −0.38 m. The St. Gowan data do not agree as well as those from the Isles of Scilly or South Uist sites and this is probably due in part to the stronger currents and larger tidal range at St. Gowan. The analysis of the results at St. Gowan is complicated owing to the presence of several simultaneous effects which modify the local wave climate. However, the effects of tidal variations on the accuracy of the model results seem to be limited to time-scales of less than a day. In general the model still successfully simulates the wave climate despite a degradation of small-scale detail.

There also seems to be no time error in the model; i.e. it follows the measured wave field well with respect to time.

For verification of the wave archive containing values for once every 12 hours, intermediate measured wave activity is not important. Peaks on the measured wave-height time series occur randomly and most take approximately 12 hours to build up and decay, so model data every 12 hours will not represent all the peaks. If it is important for the model to predict these peaks, for example if the archive is used for climatological purposes where no measured data are available, then the provision of model data every 6 hours would be required to overcome this deficiency. Obviously the shorter the interval is between model data points the better, but unfortunately there are other constraints which restrict this, such as the physical problems of producing and handling such large amounts of data.

Owing to the differences between shipborne wave recorders and waverider buoys (and between different SBWRs), especially at low wave heights, it would be an advantage if only one type of recording device is selected for future verification exercises.

Model results are very sensitive to fetch regime. Verification data exposed to short and long fetches are needed to assess the model performance fully.

## 6. Summary of conclusions

(1) The model cannot be expected to agree with observations as well in coastal areas with strong currents as it does at less tidal locations.

(2) The model is very sensitive to fetch, and long and short fetches are needed for checking purposes.

(3) Modelled wave heights follow measured values well with respect to time.

(4) If the model is to be used for climatological purposes then model data are needed at least every six hours to capture high-wave event maxima.

(5) For verification, measured data should be standardized on one type of recording instrument, preferably the waverider buoy.

## Acknowledgement

My thanks go to Mr J. J. Ephraums for his invaluable help in this work.

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# The estimation of mean temperature from daily maxima and minima

By P. Collison and R. C. Tabony

(Meteorological Office, Bracknell)

**Summary**

Departures from the true mean temperature of the average of daily maxima and minima are shown to depend on the combined effects of radiation and advection. In Britain, systematic errors are generally less than 0.3 °C, but pronounced seasonal and geographical variations are caused by changes in radiation and in the relative importance of advection. Differences between 12-hour maxima and minima read at 09 and 21 GMT and 24-hour values read at 09 GMT are also investigated, and are found to vary seasonally but not geographically.

## 1. Introduction

Mean temperatures are often calculated from the average of daily maxima and minima. This is clearly convenient, since at many stations more frequent observations, from which more reliable estimates could be made, are not available. It is clearly important, however, to have some knowledge of the errors introduced by such a procedure.

Synoptic automatic weather stations currently being introduced by the Meteorological Office record 24 hourly observations of temperature, but not maxima or minima. Since the true mean temperature is very closely approximated by the mean of 24 hourly observations, there will be no difficulties in obtaining mean temperatures for such stations. It will be important to know, however, how these compare with values derived from the averages of maxima and minima.

The problem of estimating the true mean temperature has been investigated many times before. Brooks (1921) undertook a global appraisal, but rather than quoting errors associated with the use of maximum and minimum, concentrated on finding a combination of hourly observations which gave better estimates of the true mean temperature. For the United Kingdom, he suggested a weighted mean of temperatures observed at 07, 13, and 21 GMT, these being the times at which observations were

commonly made in those days. Baker (1975) has shown that the errors in using daily maxima and minima depend upon the time at which the observations are made. If this is close to the time of the minimum, then an underestimate of the mean is made, while if it is close to the time of the maximum, then an overestimate is obtained.

The World Meteorological Organization recommends taking the mean of the day maximum in the period 09–21 GMT and the night minimum in the period 21–09 GMT, and, in the United Kingdom, this practice is followed at stations manned by Meteorological Office staff. At the 480 or so voluntary climatological stations observations are made only once per day at 09 GMT. An investigation of the differences between 12-hour (09–21 and 21–09 GMT) and 24-hour (09–09 GMT) maxima and minima based on 38 stations in the period 1957–70 was reported by the Meteorological Office (1976). It was found that differences in the summer were small, but that in the winter the 24-hour values were more extreme, with a difference of 0.4 °C for the maxima and 0.7 °C for the minima. Unpublished work in the Meteorological Office based on 14 stations in the period 1957–70 also investigated errors in the estimates of the mean of 24 hourly observations obtained by averaging the daily maxima and minima. In summer, both 12-hour and 24-hour maxima and minima were found to overestimate the mean by 0.2 °C. In winter, the 12-hour maxima and minima gave good estimates of the mean, while the 24-hour values gave means which were 0.2 °C too low. The results were stated to be similar for all the stations examined.

The present investigation essentially repeats the earlier Meteorological Office work using data from 15 stations for 1961–80. The broad results are confirmed, but the factors responsible for producing the departures from the true mean temperatures are discussed, and these are used to explain a substantial geographical variation which was not revealed in the previous analysis.

## 2. Differences between the mean of 24 hourly temperatures and the average of daily maxima and minima

The departure of the mean of maximum and minimum from the true mean will depend upon the distribution of temperature in a 24-hour period. If the temperature spends more time near the minimum than the maximum, i.e. the distribution is positively skewed, then an overestimate of the mean is made. If the skewness is reversed, then an underestimate is obtained. On any given day, the sequence of hourly temperatures will depend upon the combined effects of radiation and advection. It is changes in radiation and in the relative importance of advection which are responsible for the seasonal variations in the errors of mean temperature, and for the differences obtained from the use of either 12-hour or 24-hour values of the maximum and minimum. The relative importance of advection, however, will also be greater on coasts than inland, and in the north-west of Britain than in the south-east. This leads to the expectation that there may be geographical variations in the errors of the estimates of mean temperature. These expectations are confirmed by the analysis.

The distribution of the 15 stations used is shown in Fig. 1, and results are presented for two groups of stations. The first group — Ringway, Elmdon, Heathrow, Waddington, and Boscombe Down — represents inland stations in England, while the second group — Lerwick, Wick, Stornoway, Tiree and Valley — represents coastal sites in the north-west of Britain. Let $\Delta_9$ denote the departure from the true mean of the mean of the 24-hour maxima and minima recorded at 09 GMT, and $\Delta_{DN}$ the departure from the true mean of the day maxima and night minima recorded at 21 and 09 GMT respectively. The true mean is obtained from the average of 24 hourly observations of temperature. Monthly values of $\Delta_9$ and $\Delta_{DN}$ are presented for the two groups of stations in Fig. 2, and their distributions are seen to be quite different. At inland stations a bimodal pattern emerges, with values exceeding 0.2 °C in spring and autumn, and falling to near zero in winter. At the coastal sites, a simpler distribution, with a summer maximum and winter minimum emerges. For both groups of stations, $\Delta_9$ is similar to $\Delta_{DN}$ in summer, but lower in winter.


Figure 1. Distribution of stations used in this study.

## 3. The effects of radiation and advection

### 3.1 *Radiation*

The effects of radiation are well represented by the distribution of mean hourly temperatures, since advective effects will be self-cancelling. At coastal stations, any advective effects with a regular diurnal cycle, e.g. the sea-breeze, will also be included, but this is not important in terms of a qualitative explanation of the observed behaviour of $\Delta$.

The radiation received from the sun on a horizontal surface is proportional to the sine of the solar elevation, and is therefore more sensitive to solar elevation when the sun is low in the sky than when it is high. Thus the maximum temperature will be more sharply defined in winter than in summer, and this is illustrated in Fig. 3, which displays the mean hourly temperatures at Heathrow during June and December for 1961–80. In December, the temperature spends more time near the minimum than the maximum, the true mean is overestimated from the mean of the maximum and minimum, and $\Delta$ is positive. In June, the skewness of the temperature distribution is less marked, but is in the opposite sense, and $\Delta$ assumes a small negative value. The seasonal variation in $\Delta$ which is caused by radiation is illustrated schematically in Fig. 4(a). For most of the year, the minimum is flatter than the maximum, giving positive values of $\Delta$, and negative values are restricted to June and July. The effects of radiation at coastal sites are similar, but the seasonal variation is less marked, and $\Delta$ is close to zero in June and July.

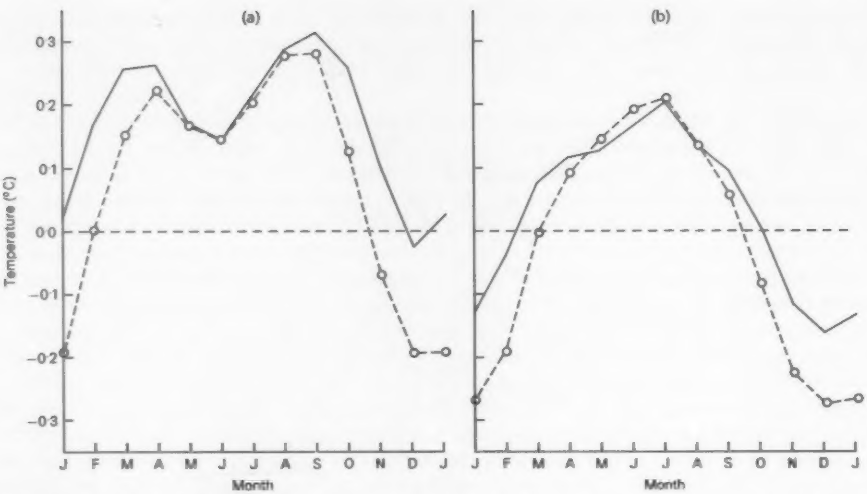


Figure 2. Departure DN from the true mean of ½ (day maximum + night minimum) temperatures recorded at 21 and 09 GMT respectively ($\Delta_{DN}$) and of the mean of the 24-hour maxima and minima recorded at 09 GMT ($\Delta_9$) for (a) inland stations and (b) coastal stations.
——— $\Delta_{DN}$   o — — — o $\Delta_9$

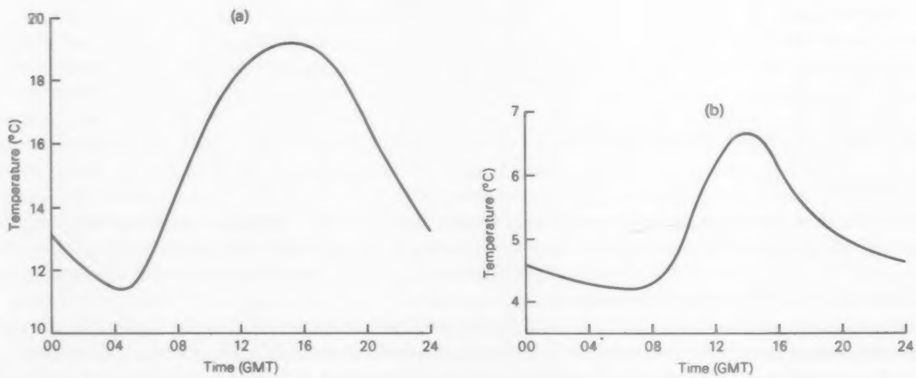


Figure 3. Mean hourly temperatures at Heathrow in (a) June and (b) December during the period 1961–80.

### 3.2 *Thermal advection*

The effects of steady thermal advection are illustrated in Fig. 5, where advective temperature changes of 1 °C every 2 hours, i.e. 12 °C in 24 hours, have been superimposed on the mean hourly temperatures for December at Heathrow. Thus, for the warm advective case, the sequence of hourly observations has been constructed by subtracting 6 °C from the mean for 09 GMT, 5.5 °C from the mean for 10 GMT,

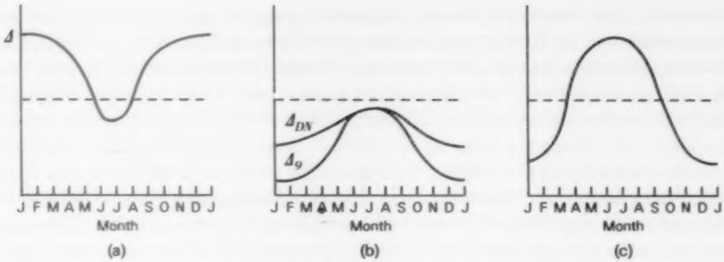


Figure 4. Contributions of (a) radiation, (b) thermal convection and (c) variable cloud cover to departure of means of maximun and minimum temperatures from true means ($\Delta$).

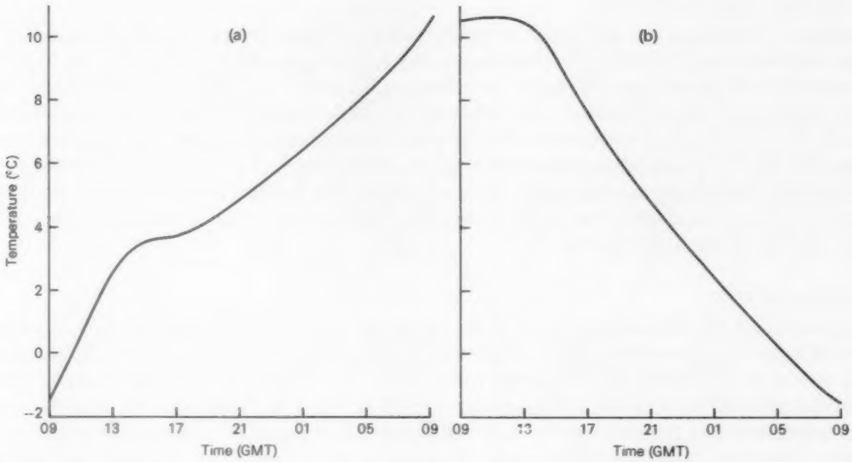


Figure 5. The effects of steady thermal advection, (a) warm and (b) cold, superimposed on the mean hourly temperatures for December at Heathrow.

5 °C from the mean for 11 GMT, and so on, finally adding 6 °C to the mean for 09 GMT the next day. The true mean temperatures for these occasions are therefore the same as in Fig. 3, but the skewness of the distribution of hourly temperatures has been radically changed. The cold advective case in particular shows that the minimum is sharper than the maximum, with a consequent underestimation of the true mean (negative $\Delta$). The warm advective case, although less obvious from the diagram, also has a negatively skewed distribution of hourly temperatures and produces the same negative value of $\Delta_9$ as the cold advective case. The difference between the cases is that in the cold advective situation, both the 12-hour and 24-hour maximum and minimum are recorded at 09 GMT, whereas with warm advection, the 12-hour values are recorded at 21 GMT. The mean of the 12-hour maximum and minimum is therefore the 21 GMT temperature, and this is close to the true mean. This is because the mean temperature at 21 GMT is close to that for the day in Fig. 3 (the 21 GMT and daily mean temperatures in Fig. 5 are the same as those in Fig. 3).

In winter, therefore, the effects of thermal advection oppose those of radiation, and produce underestimates of the true mean. The effects are greater for 24-hour than 12-hour maxima and minima. In summer, advective effects are small for two reasons. Firstly, thermal contrasts between air masses in summer are less than in winter, while the diurnal variation caused by radiation is much stronger. The result is that maxima and minima are rarely observed at 21 or 09 GMT in summer; in winter, this is not uncommon. Secondly, the observing hour of 09 GMT is close to the minimum in winter but not in summer. The results found by Baker (1975), that the errors in the true mean obtained from 24-hour maxima and minima depend on the observing hour, are due to advection. If the observing hour is close to the time of the minimum (e.g. 09 GMT in winter) one effectively has the choice of two minima; if it is close to the time of maximum, one has the choice of two maxima. If the observing hour is mid-way between maximum and minimum (e.g. 09 GMT in summer or 21 GMT at any time) then the effects of advection are minimized. The seasonal variation in the contribution of advection to $\Delta$ are illustrated in Fig. 4(b).

### 3.3 *Variations in cloud cover*

The effects of variations in cloud cover on the distribution of hourly temperatures are caused by both advection and radiation. The change in cloud cover may well be caused by advection, but the response of the temperature will depend upon the radiation balance at the time the change occurs. Consider a 3-hour cloud clearance in winter, for instance. If it occurs around midday, a slight rise may be produced, but in the long hours of darkness, it will cause a fall. This will cause a sharp minimum to be produced, and so the mean temperature will be underestimated (negative $\Delta$). In general, sensitivity to radiation is greatest at night in winter (which produces negative $\Delta$) and in daytime in summer (which produces positive $\Delta$). The contribution to $\Delta$ caused by variations in cloud cover is therefore negative in winter and positive in summer, and this is illustrated in Fig. 4(c).

### 3.4 *Combined effects*

The combined effects of radiation, thermal advection, and variable cloud cover on $\Delta$ can be obtained from an addition of the curves displayed in Fig. 4 and a qualitative explanation of the results presented in Fig. 2 is now clear. At inland stations, where radiation is relatively important, $\Delta$ is generally positive. The bimodal distribution is caused by the summer trough for radiation being sharper than the summer peak for advection and variable cloud cover. Although the response to variations in cloud cover is essentially radiative, they will occur most frequently where advective changes are common. Consequently, where advection is important, the greater weight attached to the curves in Figs 4(b) and 4(c) produces a relatively simple distribution of $\Delta$, with positive values in summer and negative values in winter. The differences betwen $\Delta_9$ and $\Delta_{DN}$ are caused by the greater advective effects in winter, and are mainly due to the close proximity of the observing hour (09 GMT) to the time of minimum temperature.

Application of these results rests on a knowledge of the extent to which the 'inland' or 'coastal' set of figures applies to any given station. The difference between the two sets may be quantified by the difference of the values of $\Delta$ in June and July from those for the whole year. This has a correlation of −0.84 with the mean annual diurnal range and −0.92 with the standard deviation of the monthly mean values of the diurnal range. This latter quantity decreases to the north-west more rapidly than the diurnal range itself. The high correlation must be considered suspect because of the difficulty of distinguishing between coastal effects and distance to the north-west — no coastal stations in the south-east or inland stations in the north-west were used. Nevertheless, the standard deviation of the diurnal range probably offers a reasonable means of deciding how the values of $\Delta$ pertaining to a particular station compare with the two sets presented in Fig. 2. A generalized map of the standard deviations of

the mean monthly values of diurnal range, based on nearly 600 stations in the period 1951–80, is presented in Fig. 6. The quoted values of $\Delta$ for the sets of inland and coastal stations are associated with standard deviations of 1.4 °C and 0.5 °C respectively. Fig. 6 therefore shows that values of $\Delta$ associated with a standard deviation of 1.4 °C are probably representative of a large proportion of the country, while those associated with a standard deviation of 0.5 °C are likely to be restricted to the more exposed coastal sites in the north and west.

The difference between the true mean and that obtained from the maximum and minimum on any given day may, of course, vary widely from the values presented above. The standard deviation of both $\Delta_9$ and $\Delta_{DN}$ in all months is around 0.5 °C. The assumption that there are 10 independent values in 31 daily measurements of temperature suggests that the standard errors to be attached to the quoted values of $\Delta$ is around 0.03 °C, but that the standard deviation of $\Delta$ for individual months is 0.16 °C.


Figure 6. Standard deviation of monthly mean values of diurnal range of temperature (°C) for the period 1951–80.

### 4. Differences between 12-hour and 24-hour maxima and minima

Thermal advection and variable cloud cover are responsible for introducing the differences between the 12-hour (09–21 and 21–09 GMT) and 24-hour (09–09 GMT) maxima and minima. Fig. 7 shows that the differences are greater in winter than in summer, and for minima than maxima; these features may be attributed to the dominance of radiation in summer and the proximity of the observing hour (09 GMT) to the time of minimum temperature in winter. Geographical variations in these differences may be anticipated. The greater importance of advection on north-western coasts contributes towards larger differences there than elsewhere, but this is counteracted by the greater radiative response to variable cloud cover at inland sites, especially for minima in winter. As a consequence, differences between maxima are likely to be largest on north-western coasts, while in winter, differences between minima are likely to be greatest inland. While such geographical variations are present and are indicated in Fig. 7, the effects are generally small, and do not assume any great practical importance. The findings of the Meteorological Office (1976) concerning the differences between 12-hour and 24-hour maxima and minima are therefore confirmed, both in respect of the size of the differences attained and in the relative absence of geographical variations.

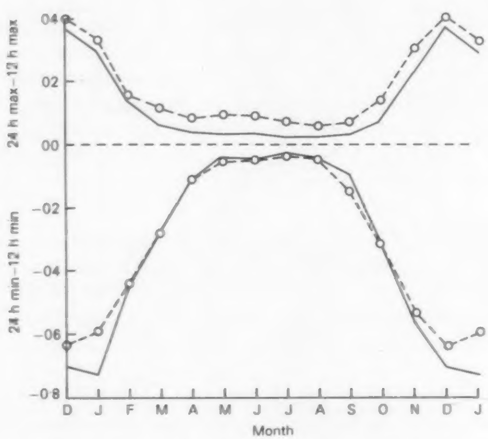


Figure 7. Differences between 12-hour and 24-hour maximum and minimum temperatures at inland stations (———) and coastal stations (o — — — o).

### 5. Conclusions

The difference between the mean of daily maxima and minima and the true mean temperature has been shown to depend on the effects of radiation and advection. The regular diurnal variation of radiation causes the mean of the maximum and minimum to overestimate the true mean in winter, but this difference is generally opposed by the effects of thermal advection. Irregular variations in cloud cover cause the true mean to be overestimated in summer but underestimated in winter. The combined effect of these factors depends on the relative importance of advection, and this varies widely with location. Where radiation is relatively important, as in inland stations in the south-eastern half of

Britain, the departure of the mean of day maximum and night minimum from the true mean undergoes a bimodal seasonal variation, with maximum differences around +0.2 °C in spring and autumn. Where advection is more important, differences range from +0.2 °C in summer to −0.2 °C in winter. The relationships previously found between 12-hour and 24-hour maxima and minima were confirmed, with only small geographical variations evident.

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| | | |
|---|---|---|
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## A comparison of daily maximum and minimum temperatures with the highest and lowest of 24 hourly observations

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(Meteorological Office, Bracknell)

**Summary**

Automatic weather stations designed solely to make synoptic observations do not report maximum and minimum temperatures, so these parameters have to be estimated from the highest and lowest of hourly observations. The mean difference between the two types of observation was found to be around 0.4 °C, but values at some stations were twice as great as at others, and occasional differences of 2 °C were found. No coherent geographical variations were identified, but the difference between the maximum and the highest hourly observation was twice as great in summer as in winter.

### 1. Introduction

The Meteorological Office is developing two principal types of automatic weather station, one for making synoptic observations (SAWS), and the other for obtaining climatological data (ACRE). Platinum resistance thermometers housed in Stevenson screens will be used to record temperatures in both systems, with 'one-minute' observations being computed from instantaneous measurements made every 5 seconds. Hourly temperatures will be based on the last 5 such observations preceding the hour and, in synoptic stations, these recordings will be capable of immediate onward transmission. A facility to extract maximum and minimum temperatures from the one-minute observations will be included in the climatological, but not the synoptic, type of station. For the synoptic station, therefore, only the highest and lowest of the hourly observations will be available. It is therefore desirable to have a knowledge of the difference between the maxima and the minima recorded by the two types of automatic station and the conventional manned site in order that direct comparison between the different types of observation may be made.

The response times of platinum resistance and mercury-in-glass thermometers are similar at around 30 seconds. The maxima and minima derived from the one-minute observations at automatic climatological stations are therefore likely to be similar to those obtained from conventional sites. In this

paper the likely differences between these values and the most extreme hourly temperatures obtained from automatic synoptic stations are investigated by examining the differences between the conventional maxima and minima and the highest and lowest of hourly observations recorded at manned stations. Hourly observations from the automatic weather stations will be less variable than those obtained manually because the former represent a temperature averaged over 5 minutes instead of, say, 30 seconds. If the difference between the maxima and the highest hourly observations is denoted by $D_H$, and that between the minima and the lowest hourly observations is represented by $D_L$, this implies that the variability of $D_H$ and $D_L$ will be less for automatic than for manned stations, although their mean values will be the same.

## 2. The data and their quality control

Hourly temperature observations together with maxima and minima recorded in the period 09–09 GMT were extracted for the years 1971–80 for 16 stations whose distribution is shown in Fig. 1. Data for earlier years were available, but not used because they were less well quality controlled. In the calculation of $D_H$ and $D_L$, values less than zero were replaced by zero, while values exceeding 3°C were ignored. Cases in which the maximum or minimum occurred at 09 GMT were excluded from the analysis, as on those occasions either $D_H$ or $D_L$ would be zero.

From 1974 to 1980, data for the conventionally exposed thermometers were supplemented by observations from the aspirated psychrometer and North Wall Screen at Kew; these are analysed separately in section 7.

## 3. Relations between $D_H$ and $D_L$ and fluctuations in hourly temperature

The simplest means of estimating maxima and minima from the highest and lowest of hourly observations is to assume a constant difference between them. The possibility exists, however, that these differences depend on certain aspects of the weather, and that this dependence can be used to improve the estimates of the maxima and minima. Investigations into the possibilities were restricted to attempts to relate $D_H$ and $D_L$ to features of the hourly temperature record.

The first attempt was to fit a quadratic temperature profile to the extreme hourly and two adjacent observations, and to note the turning points of the parabolic curves. At Elmdon, however, these turning points only differed from the most extreme hourly observations by 0.05 °C, and the variance of the difference between them and the maximum and minimum was scarcely reduced below the variance of $D_H$ and $D_L$.

The second attempt was to regress $D_H$ and $D_L$ against $T_H$, $T_L$, $T_h$ and $T_l$ where

$T_H$ = difference between the highest and second highest hourly temperatures,

$T_h$ = difference between the highest hourly temperature and the mean of the adjacent observations

and $T_L$ and $T_l$ are similarly defined with respect to the lowest hourly temperature. For each of the 16 stations, however, none of the regressions had correlations which much exceeded 0.2.

The reasons for the failure of these attempts must be that the maxima and minima are produced by fluctuations of temperature on a time-scale of much less than an hour, and that these fluctuations bear little relation to the differences between hourly observations.

## 4. Mean values of $D_H$ and $D_L$

Mean values of $D_H$ and $D_L$ were found to be 0.36 °C and 0.41 °C respectively but, over the 16 stations examined, values ranged from 0.25 °C to 0.48 °C for $D_H$ and 0.30 °C to 0.58 °C for $D_L$. These differences, however, seemed to depend on local site peculiarities, and no large-scale variation, either with latitude or


Figure 1. Distribution of stations used in this study.

distance from the coast, could be identified. The dependence of $D_H$ and $D_L$ on local factors is supported by the fact that stations with high values of $D_H$ tended to be associated with low values of $D_L$, and vice versa ($r = -0.45$). Large values of $D_L$ occur at sheltered sites which favour the development of strong nocturnal inversions, while large values of $D_H$ are more likely to occur at exposed sites where turbulence is stronger.

Mean monthly values of $D_H$ and $D_L$, averaged over the 16 stations, are represented in Fig. 2, together with figures for the stations with the highest and lowest annual means. A pronounced seasonal variation is revealed for $D_H$, with values close to 0.2 °C in winter and 0.5 °C in summer. This variation, which is caused by increased convection and gustiness in summer, is fairly general, and the ratio of summer to winter values is similar for all stations. In contrast, nocturnal conditions show little in the way of seasonal differences, and $D_L$ remains close to 0.4 °C.

## 5. The variability of $D_H$ and $D_L$

The variability of $D_H$ and $D_L$ is illustrated for a typical station, Elmdon, for which the means of $D_H$ and $D_L$ are close to those for the average over 16 stations. Fig. 3 displays the frequency distribution of $D_L$ for the whole year, and of $D_H$ for summer (May–August) and winter (November–February). A generally

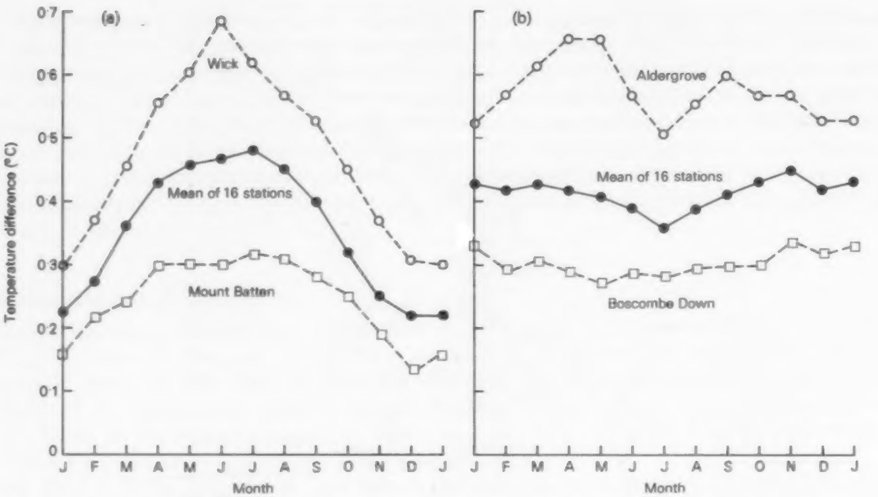


Figure 2. Seasonal variation of the mean values of the difference between (a) 24-hour maxima and highest hourly temperatures ($D_H$) and (b) 24-hour minima and lowest hourly temperatures ($D_L$).

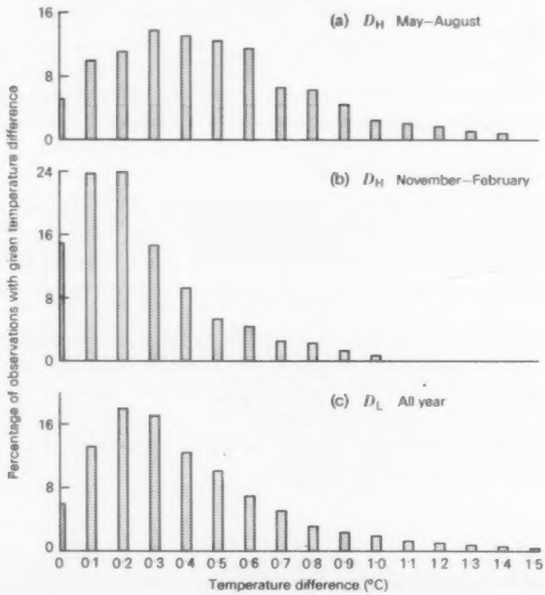


Figure 3. Frequency distribution of the difference between 24-hour maxima and highest hourly temperatures ($D_H$) and 24-hour minima and lowest hourly temperatures ($D_L$) at Elmdon.

skew distribution is apparent so that, although the mean of $D_L$ is 0.4 °C, the mode is 0.2 °C and occasional values of 1.5 °C are attained. The skewness of $D_H$ in summer is generally less, but values of 1.5 °C are still possible. For some stations, for which the means of $D_H$ and $D_L$ may exceed those at Elmdon by 50%, occasional values in excess of 2 °C must be expected. It should be recalled, however, that the variability of $D_H$ and $D_L$ will be less for automatic than conventional observations because of the long averaging period (5 minutes) of the automatic hourly observation.

### 6. 12-hourly maxima and minima

The above analysis has compared differences between the maximum and minimum and the highest and lowest of hourly observations in the 24-hour period 09–09 GMT. This analysis was repeated using data for the 12-hour periods 09–21 and 21–09 GMT. Differences between the day (09–21 GMT) maximum and the highest hourly observation, and the night (21–09 GMT) minimum and the lowest hourly observation, were found to be very similar to $D_H$ and $D_L$ for 24-hour maximum and minimum. The main difference between the night maximum and the highest hourly observation was only 0.2 °C, while that between the day minimum and the lowest hourly observation was mostly 0.4 °C, but nearer to 0.3 °C from July to September.

### 7. The aspirated psychrometer and North Wall Screen at Kew

The sensitivity of $D_H$ and $D_L$ to the precise siting and nature of the instruments is illustrated by an examination of their values for the aspirated psychrometer and North Wall Screen at Kew. A full description of the site and instrumental details are given by Painter (1970),* but the main non-standard features are the forced ventilation of the psychrometer and the excessive height, 5 metres above most of the ground, of the North Wall Screen.

Mean monthly values of $D_H$ and $D_L$ for the two sites are displayed in Fig. 4. Comparison with Fig. 2

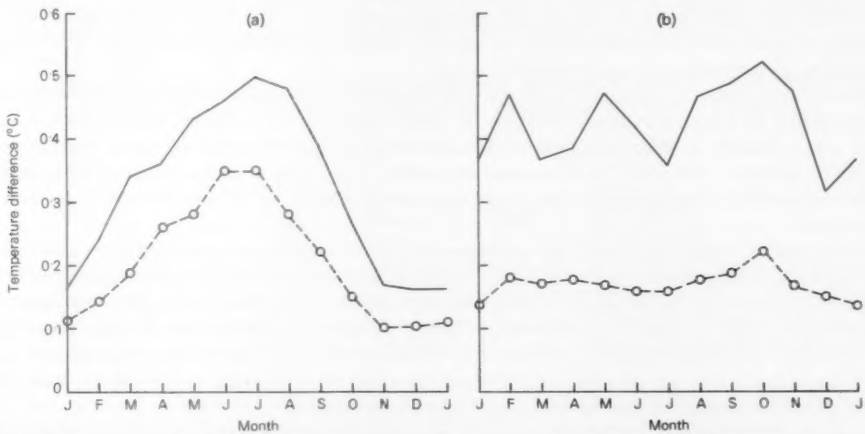


Figure 4. Mean monthly values of the difference between (a) 24-hour maxima and highest hourly temperatures ($D_H$) and (b) 24-hour minima and lowest hourly temperatures ($D_L$) at Kew. The higher values are from the aspirated psychrometer and the lower values are from the North Wall Screen.

*Painter, H.E.; A recording resistance psychrometer, *Meteorol Mag*, **99**, 1970, 68–75.

shows that the figures for the aspirated psychrometer are typical of those for standard instruments, while those for the North Wall Screen are much lower, especially for $D_L$. The reduced amplitude of the short-period fluctuations of temperature in the North Wall Screen can be mainly attributed to the excessive height of the thermometers above the ground.

## 8. Conclusion

Differences between daily maximum and minimum and the highest and lowest of 24 hourly observations at conventional stations are of the order of 0.3 to 0.4 °C. Values at some stations are twice as great as at others, but there is no coherent geographical variation. The difference between the maximum and the highest hourly observation undergoes a marked seasonal variation, with mean values ranging from 0.2 °C in winter to 0.5 °C in summer. The frequency distribution of the daily values is skewed, with occasional differences of 1.5 °C possible at a typical station and 2 °C at some. The range of values at automatic weather stations, however, will be less than this because of the long averaging period (5 minutes) of the hourly observation. The sensitivity of the differences to local site and instrumental detail are illustrated by observations from the aspirated psychrometer and North Wall Screen at Kew.

# Reviews

*Variations in the global water budget*, edited by Alayne Street-Perrott, Max Beran and Robert Ratcliffe. 165 mm × 245 mm, pp. xiv + 518, *illus*. D. Reidel Publishing Company, Dordrecht, 1983. Price US $69.50.

This volume contains 32 papers presented at the Symposium of the same name held at Oxford in August 1981. The stated purpose of the book is to 'act as a state-of-the-art summary of material on the hydrological cycle, with emphasis on its variability'. There are contributions from climatologists, hydrologists, glaciologists and palaeoclimatologists.

Papers are grouped in five sections with brief introductions to each section. The first two sections deal with techniques of measurement and analysis of water budgets in the atmosphere and on the earth's surface. They include a major analysis of the distribution and transport of water vapour in the atmosphere (Peixóto and Oort) and a clear and valuable summary of our present knowledge of evaporation models (Shuttleworth). There are also several papers on remote sensing of rainfall and water vapour.

The next section deals with variability on timescales from months to hundreds of years and includes papers on rainfall fluctuations in Africa, India, China and Australia. Nicholson and Chervin stress the synchronous occurrence of drought in both hemispheres in Africa and the spatial coherence and persistence of rainfall anomalies in sub-Saharan zones. Almost three years later drought continues in West Africa giving added urgency to the need to investigate further the possible feedbacks between rainfall fluctuations and the general circulation as, for example, presented here by Reiter who relates equatorial Pacific rainfall to the Northern Hemisphere circulation.

Long-term changes during the late Quaternary period are the subject of the next section. These papers cover a wide series of topics, e.g. late glacial circulation over North America, evaporation from Lake Chad and possible atmosphere – ocean feedback mechanisms.

The final section, comprising papers on modelling and prediction, indicates the substantial progress made in recent years in the development of global climate models. Undoubtedly, progress in

understanding and predicting climatic fluctuations must come from the development of such models, but it is possible that economically useful seasonal predictions could be made from our present knowledge of teleconnections and persistence. An assessment of the possibilities would have been a valuable addition. Sadly, the book has no mention of the social and economic importance of variations in water budget components, giving the unfortunate impression that the field is scientifically interesting and active but not of great practical importance.

However, the book succeeds in its purpose and will be a useful addition to any meteorological library and a valuable reference book for students, though I do not see it becoming an undergraduate textbook as the publishers suggest. Editors and publishers must be congratulated on producing an attractive and error-free book with excellent layout and diagrams.

M. D. Dennett

*A first course in fluid dynamics*, by A. R. Paterson. 155 mm × 232 mm, pp. vi + 528, *illus*. Cambridge University Press, 1983. Price £30.00 (paperback £12.50).

This excellent book is based on a lecture course given to second-year honours mathematics students at Bristol University. It was written after the author had formed the opinion that 'the modern texts with the "right" attitude to the subject were too hard for a first course and the older texts were dominated by potential theory and unrealistic examples'.

The first eight chapters deal with mathematical, physical and observational preliminaries, mass conservation and stream functions, vorticity, hydrostatics, thermodynamics and the equations of motion. The remainder of the book discusses solutions to a variety of problems that theoretical dynamicists have to deal with in their studies of flows over a wide range of Reynolds number and Mach number, including flows past obstacles, channel flows, sound waves, water waves, supersonic flows and aerofoil theory. Each chapter ends with a set of useful exercises, answers to and hints for the solution of which are provided at the end of the book, where the author also thoughtfully provides a list of reference books and an index.

The book contains little of direct relevance to meteorologists but it will have a wide appeal amongst scientists in many disciplines who are interested in the fundamentals of fluid dynamics.

R. Hide

## Books received

*Future weather*, by John Gribbin (Harmondsworth, Penguin Books, 1983, £3.50). The author analyses here the causes and effects of climatic change, relating them to the 'greenhouse effect', and asks what the implications are for the utilization of energy for agriculture and for global and local politics. He also considers the evidence that the climatic balance of our world is being destroyed by our short-sighted activities.

*Remote sensing applications in marine science and technology*, edited by Arthur P. Cracknell (Dordrecht, D. Reidel Publishing Co., 1983, US $78.00) contains the proceedings of the NATO Advanced Study Institute on Remote Sensing Applications in Marine Science and Technology, held in Dundee, Scotland 1–21 August, 1982. The main topics covered are: the general principles of remote sensing with particular reference to marine applications; applications to physical oceanography; marine resources applications; and coastal monitoring and protection.

*Atmospheric diffusion* (third edition), by F. Pasquill and F. B. Smith (Chichester, Ellis Horwood Ltd., 1983, £35.00) is a study of the dispersion of windborne material from industrial and other sources. It covers two main areas of considerable practical interest: localized industrial air pollution in urban environments and the long-range transport of pollution to areas which are particularly sensitive to resulting depositions.

*Human response to tropical cyclone warnings and their content: World Meteorological Organization Tropical Cyclone Programme No. 12* (Geneva, WMO, 1983, free) is a study of the present terminology used for warning messages and of present knowledge and experience of its impact upon the behaviour of the population in cyclone-prone areas. The document is published in loose-leaf form so that new relevant material may be added from time to time as researchers and operational meteorologists gain greater insights into human response to natural hazard warnings.

*Tornados, dark days, anomalous precipitation, and related weather phenomena; Earthquakes, tides, unidentified sounds and related phenomena; Rare halos, mirages, anomalous rainbows and related electomagnetic phenomena;* compiled by William R. Corliss (Glen Arm, The Sourcebook Project, 1983, US $11.95) are three volumes in the series *A catalog of geophysical anomalies*, and are sister volumes to *Lightning, auroras, nocturnal lights, and related luminous phenomena,* a review of which was published in *Meteorological Magazine,* **113**, 242–243.

## Honour

Mr J. B. Lawson (Senior Scientific Officer), formerly Senior Meteorological Officer at Cranwell, now at Headquarters, has been awarded the Air Officer Commanding-in-Chief's Commendation in the Queen's Birthday Honours List. The award has been made in recognition of Mr Lawson's personal contribution to the work of RAF Cranwell.

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NOTICE

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ and marked 'For Meteorological Magazine'.

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